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ELASTIC PROPERTIES OF A TUNGSTEN - SILVER COMPOSITE ABOVE AND BELOW THE MELTING POINT OF SILVER

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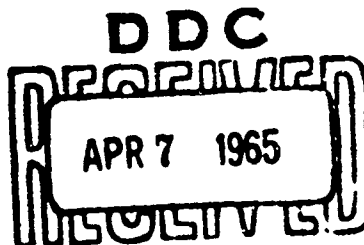
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SUMMARY

The dynamic Young's modulus of a composite of tungsten containing twenty volume percent silver was evaluated up to 1020°C . In the temperature range 25°C to 800°C , it was shown that the temperature dependence of the modulus as well as the absolute value of the modulus is closely approximated by the upper bound theory of Hashin and Shtrikman. Above 800°C the modulus decreases much more rapidly than predicted by the theory. This rapid drop in modulus is believed to be associated with interphase boundary shearing between the tungsten and silver phases. A large discontinuity in modulus (over 10% change) is observed at the melting point of silver. Above the melting point of silver the modulus of the composite is about equal to the modulus of a tungsten sample containing an equivalent percentage of pores suggesting that there is no strengthening of tungsten from the presence of molten silver.

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The prediction of elastic properties of composite materials has been the subject of a number of papers. Paul's method (PAUL, 1960) is based on the use of energy theorems of elasticity theory. The method leads to evaluating upper and lower bounds to the predicted modulus of two-phase composite materials. The upper bound is obtained when a constant strain field is assumed to exist in the composite (theorem of minimum potential energy). The lower bound is obtained when the condition of constant stress is imposed on the composite (theorem of least work). The limiting values obtained are generally quite far apart and permit only a fair estimate of the effective modulus of a composite body. HILL (1963) has critically analyzed the status on elastic behavior of composite materials and has pointed out some of the inadequacies of the Paul theory. WU (1964) has considered the influence of the shape of the discontinuous phase on the elastic behavior of composite bodies. The author showed that disk-like particles are best, needle-like particles second best and spherical particles the least desirable from the viewpoint of increasing the modulus of a soft matrix with hard inclusions. HASHIN AND SHTRIKMAN (1963) have applied variational principles in the linear theory of elasticity to predict elastic moduli of multiphase materials. Their results lead to prediction of upper and lower bounds of moduli that are contained well within the bounds given by the theory of Paul. The theoretical predictions of Hashin and Shtrikman await experimental confirmation, although room temperature modulus data for the WC-Co system (NISHIMATSU AND GURLAND, 1960) seem to fit in rather well within the limits of the theory.

It was thought that a study of the temperature dependence of the dynamic modulus for a composite material would provide a rather critical check of the Hashin-Shtrikman theory. A W-Ag composite was selected because of the rather large difference in modulus of the two base metals and because the ratio $\frac{E_W}{E_{Ag}}$ is a strong function of temperature changing from about 4.5 at room temperature to about 9 near the melting temperature.

Dynamic modulus measurements were made on a W-Ag sample containing 20 volume percent silver. This composite is obtained by first preparing a porous compact of tungsten by powder metallurgy techniques using isostatic pressing and sintering in a hydrogen atmosphere. The porous body is then infiltrated with molten silver also in a hydrogen atmosphere. The method of infiltration is by capillary action. Hence, the type of microstructure consists of two interpenetrating continuous phases, - tungsten and the infiltrant metal. Although silver wets tungsten it is believed that there is no solubility of silver in tungsten and therefore one is only concerned with pure tungsten and pure silver. In actuality, infiltration is never 100 percent efficient and density measurements revealed that the tungsten matrix in the composite sample studied contained about 1% pores. The infiltrant metal also contains pores. This is because silver shrinks about five percent upon solidification from the infiltration temperature and then contracts several times more rapidly than tungsten with decreasing temperature; at room temperature the porosity in silver amounts to about 10%. Microstructures of the composite sample investigated are shown in Figures 1 and 2. Fig. 1 illustrates the occasional porosity observed in the tungsten matrix and Fig. 2 illustrates the uniformly distributed voids in the silver region.

In order to calculate the predicted modulus of the W-Ag composite

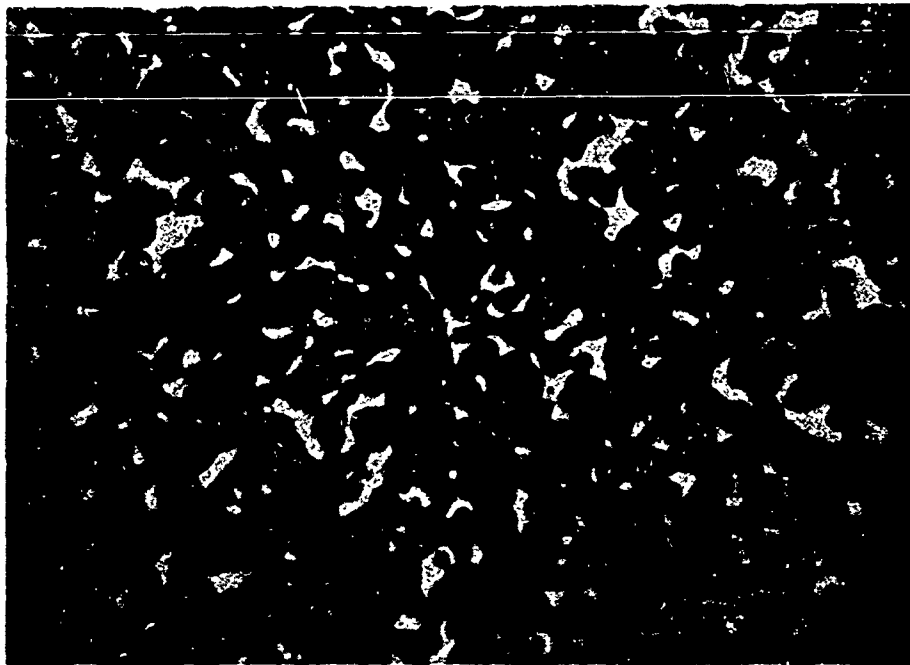


Fig. 1 Photomicrograph of silver infiltrated tungsten showing occasional uninfiltrated pores (small dark areas) in tungsten matrix. The light regions are silver and the gray regions are tungsten. Magnification is 500X. Murakami's etching reagent used.



Fig. 2 Electron photomicrograph of silver region surrounded by tungsten matrix. The fine pores in silver were obtained by shrinkage during cooling from the infiltration temperature. The width of the silver region shown is about .004 mm. Murakami's etching reagent was used.

it was necessary to evaluate the modulus of pure tungsten and pure silver. In addition, a sample of tungsten containing about the same porosity as the amount of silver present was also evaluated. The materials used are described in Table 1. All modulus measurements were determined by the both-ends-free transverse vibration method. The apparatus and experimental set-up were similar to those described elsewhere (LYTTON, HREN, KAMBER AND SHERBY, 1964) and hence their description will not be repeated here. The samples tested were in the form of rectangular bars (approximately 4" x 0.25" x .08") and the fundamental resonant frequencies determined were typically in the range 700 to 1500 cycles per second. The modulus - temperature curves for the four samples tested are given in Figure 3. The W-Ag sample was tested up to 1020°C which is 60°C above the melting point of pure silver. As can be seen, there is a sharp discontinuity in the modulus at 960°C (Fig. 3B).

It was mentioned previously that both phases in the W-Ag composite contain pores. It was therefore necessary to modify the values given for pure tungsten and pure silver in Fig. 3 to the conditions existing in the W-Ag sample studied in order to properly calculate the modulus of the composite from the various theories. This was done by applying the analysis of MACKENZIE (1950) on the influence of spherical pores on elastic properties of solid bodies. Mackenzie's relation has been shown to be valid for real systems (COBLE AND KINGERY, 1956). Since silver expands more rapidly than tungsten with increasing temperature it was assumed that the amount of porosity in silver decreased linearly with increasing temperature reaching a value of 5% right below the melting point of silver. The predictions of Hashin and Shtrikman require a knowledge of Poisson's ratio, ν , for the pure metals. Poisson's ratio of 0.28 was used for tungsten and 0.38 for

TABLE I

Description of Materials Used for Dynamic Modulus Studies

Material	Density, gms/cc	Grain Size, mm	Heat Treatment Prior to Testing	Remarks
A. Pure Tungsten (99.9%)	19.24	Fibrous Structure	None	Finish forged at about 1260°C
B. Tungsten Silver Composite (20 vol.%Ag)	17.1	0.02 (Tungsten matrix)	None	Composite was chemi- cally analyzed to con- tain 11.1 weight per- cent silver. The tungsten was 99.9% pure and the silver was 99.99% pure.
C. Porous Tungsten (17.5% porosity)	15.88	0.02	None	Sintered at about 2100°C.
D. Pure Silver (99.99%)	10.49	0.5	30 minutes at 930°C	Received in rolled sheet form.

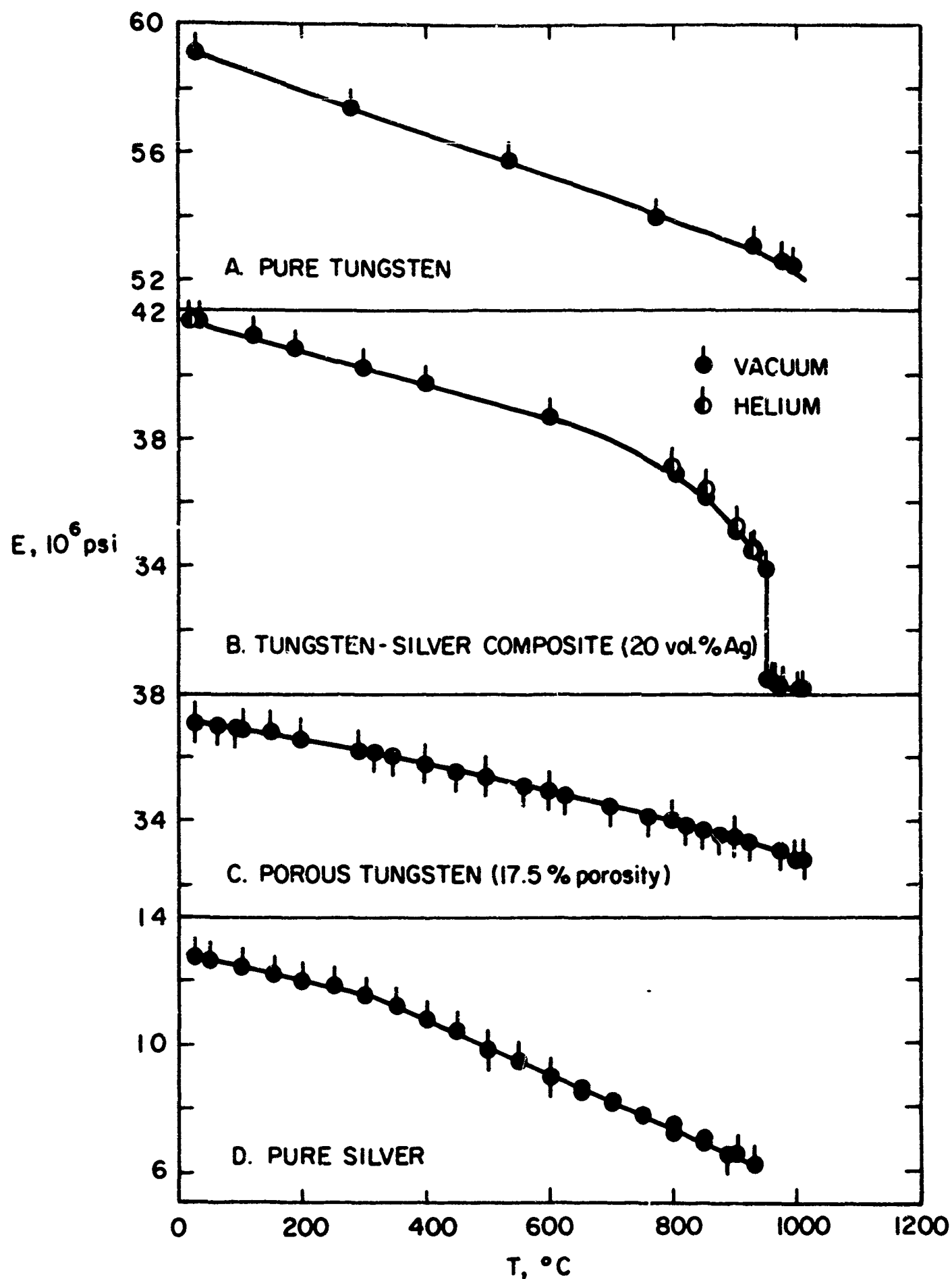


Fig. 3. Influence of temperature on Young's modulus of pure tungsten, tungsten-silver composite, porous tungsten and pure silver. The lines above or below the symbols represent values obtained on heating or cooling, respectively.

silver, and was taken to be invariant with temperature. This assumption is probably quite reasonable since FRANZ and KOSTER (1961) report only slightly increasing values of Poisson's ratio with increasing temperature for a number of pure metals. Unpublished data on Poisson's ratio for tungsten (LOWRIE, 1961) show that ν increases from 0.282 at room temperature to 0.296 at 800°C. No data appear available for silver. It is to be pointed out, however, that minor changes in the value of Poisson's ratio do not seriously influence the values of modulus as predicted from the Hashin - Shtrikman theory.

The predictions of Paul as well as of Hashin and Shtrikman are compared with the experimental data in Figure 4. As can be readily seen the upper bound curve of Hashin and Shtrikman most nearly fits with the experimental data. This particular theoretical curve is based on the assumption that spherical silver particles are completely surrounded by a hard continuous matrix of tungsten. This situation is approached in the W-Ag composite chosen for study since there is so much more tungsten than silver. It must be remembered, however, that in actuality, the silver phase is also continuous.

The fractional drop in modulus with temperature is plotted in Fig. 5. As can be seen the agreement between experiment and the upper bound theory of Hashin and Shtrikman is remarkably good up to 800°C. It is believed that these results support the general validity of the Hashin-Shtrikman approach. Above 800°C the actual modulus drops much more rapidly with temperature than is predicted from the theory. It is believed that this drastic change in modulus with temperature is due to a relaxation phenomena. It is possible that the drop is associated with interphase boundary shearing between the tungsten and silver phases simi-

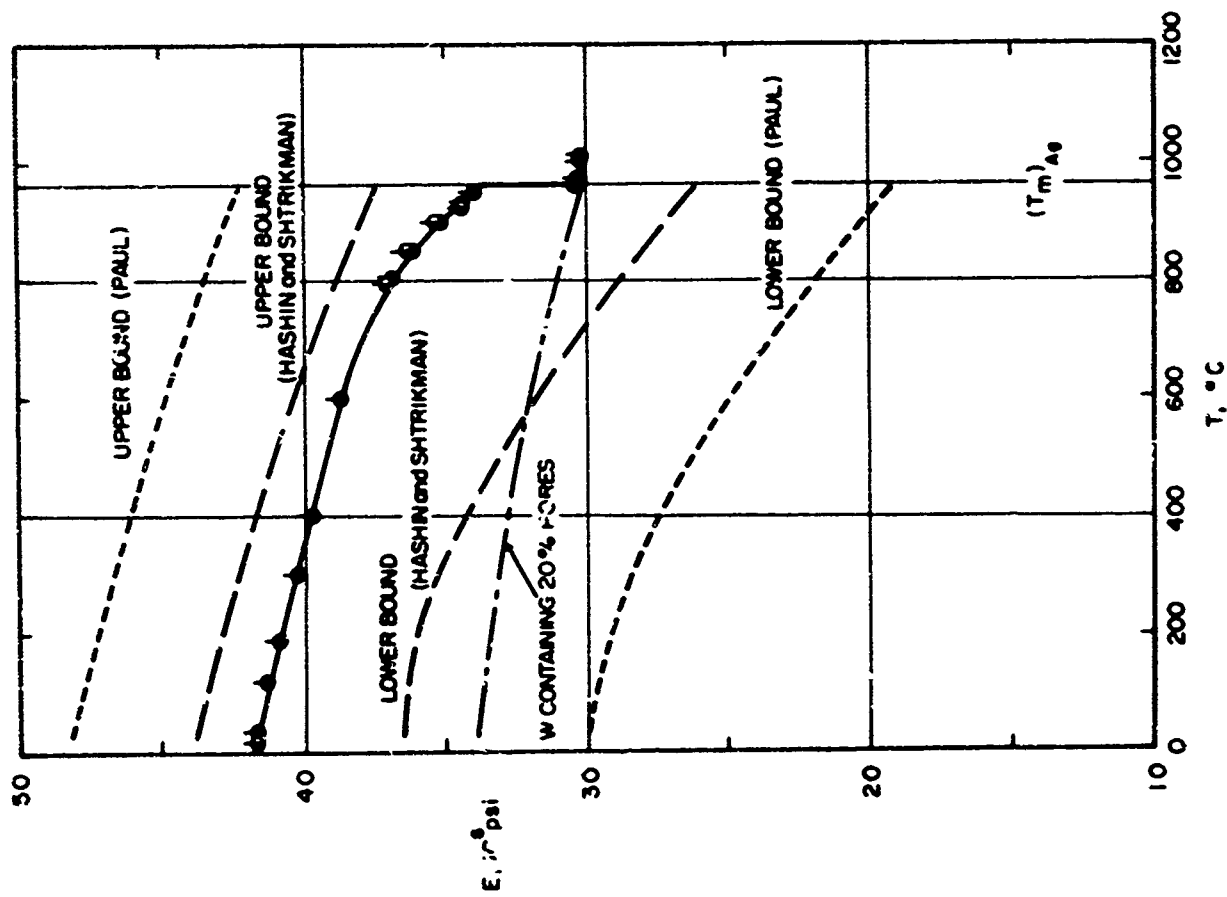


Fig. 4. Comparison of the modulus-temperature data for tungsten containing 20 volume percent silver with the theories of Paul (1960) and of Hashin and Shtrikman (1963). The extrapolated modulus of tungsten containing 20% pores is also shown.

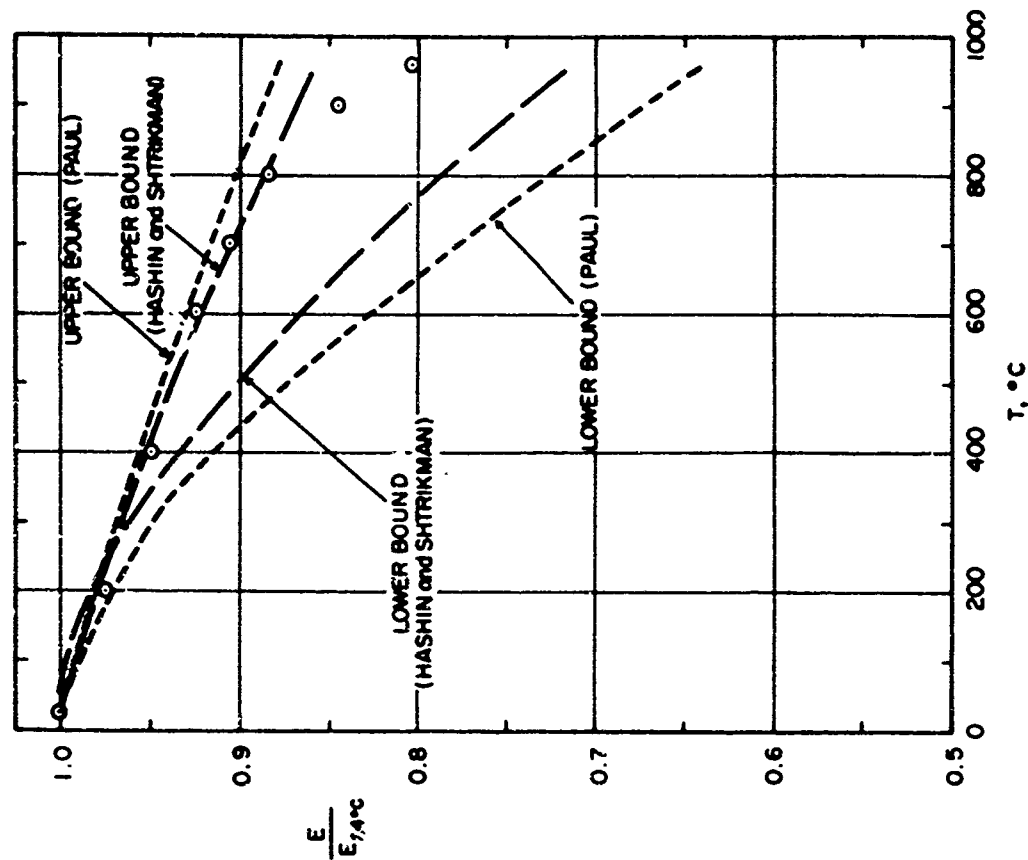


Fig. 5. Relative drop of modulus with temperature for tungsten containing 20 volume percent silver compared with the theories of Paul (1960) and of Hashin and Shtrikman (1963).

lar to the large drop in modulus observed in grain boundary shearing (ZENER, 1948). The unusual effect observed warrants additional attention. KOSTER AND BANGERT (1951) noticed a similar drop in the modulus shortly before reaching the eutectic temperature in alloys of the system Cu-Pb and Ag-Pb.

The discontinuity in modulus of the W-Ag composite at the melting temperature of silver (Figs. 3 and 4) is quite expected, and serves to show the strengthening effect of solid silver in contrast to molten silver. The elastic modulus of the W-Ag composite is compared with the modulus of a tungsten sample that would contain a comparable amount of voids (twenty volume percent) in Fig. 4. The porous tungsten curve was obtained by a linear extrapolation of the tungsten data shown in Fig. 3C (17.5 vol. percent pores) to twenty percent pores. As can be seen, there is virtually no strengthening of the tungsten from the presence of molten silver. These results suggest that the molten silver is quite free to move in the tungsten sample when under stress.

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